

Comparative Study between Design Methods and Pile Load Tests for Bearing Capacity of Auger-drilled PHC Piles

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ABSTRACT

Although a number of static pile load tests have been performed in this country, re-consideration on the interpretation and loading method is needed, because of their less usefulness in practice. Therefore, this study was focused on the finding of suitable methods for estimating bearing capacity to the prestressed high-strength concrete piles installed by SDA method. For this study, various tests which are composed of a static loading test including load transfer, PDA were systematically carried out at the whole depths of embedded PHC piles. As the results, the bearing capacities calculated by various methods were compared with the PDA and static load testing.

1. INTRODUCTION

Understanding the importance of substructure has been increased as a scale of domestic construction work has been enlarged and the form of structure has become complex. Safety of settlement and adequate bearing capacity of substructure are required according to the extension and precision of the structure. Therefore, it has been increased the use of pile foundation for railroads, highways and buildings. However using the pile construction with driving, due to the economical efficiency, has occurred environmental pollution and people had difficulties in proceeding construction. It has been changed from driving pile method to embedded pile method which is building a pile after boring in order to prevent a loud noise and other pollution from the construction.

Domestically, a precast pile is divided into a PHC pile and a steel pipe pile. Recently, because of PHC pile's durability, high strength, enlargement of diameter and an increase in the price of structural steels, it has been used broadly not only for foundation of structure but also for highway construction. In this study, through a test construction and a loading test about PHC pile($\varnothing 600\text{mm}$, $t=90\text{mm}$) applied to bridge foundation of OO construction project, we estimated methods for calculating the bearing capacity through the load supporting of an embedded pile and by dynamic loading test.

In terms of embedded pile construction, by using SDA(Separated Doughnut Auger) method, we injected grout after boring, inserted a pile, and made the end of the pile penetrate slime and fixed in-situ by slight driving.

Also, in order to investigate load transfer characteristics of the embedded pile, we set up strain gauge on steel cable in advance, when building a PHC pile, poured concrete, and measured end bearing capacity and the load of pile through a static loading test to take shaft resistance.

Moreover, as time elapsed right after the pile construction and an initial dynamic loading test(EOID), we operated a dynamic loading test(Restrike) to establish standards of construction management by comparing setup effects with the static loading test.

2. CONDITIONS OF THE GROUND

Location of the pile loading test is on the west side of Miho stream, where alluvium layer is distributed widely, and this place is indicated as a flooding area on pale geography. Currently, artificial levees are built along with the Miho stream and the location of the test has been used as paddies.

When it comes to the geotechnical profile of the area, there is a sedimentary layer containing silty clay and gravelly sand from the upper(0~3.5m), and containing sandy gravel at the bottom(3.5~7.8m). There is a weathered soil layer, approximately 6.0m, consisting of silty sand and weathered rock layer at the bottom.

0.0~3.5m of the upper sedimentary layer is sorted as a soft soil layer with the value of N 4~10 and 3.5~7.8m of the part is seen moderately dense as a value of N 15~31. Weathered soil is over than a value of N 50 which is very stiff. This test pile is embedded 1.2m into the bottom of the weathered rock.

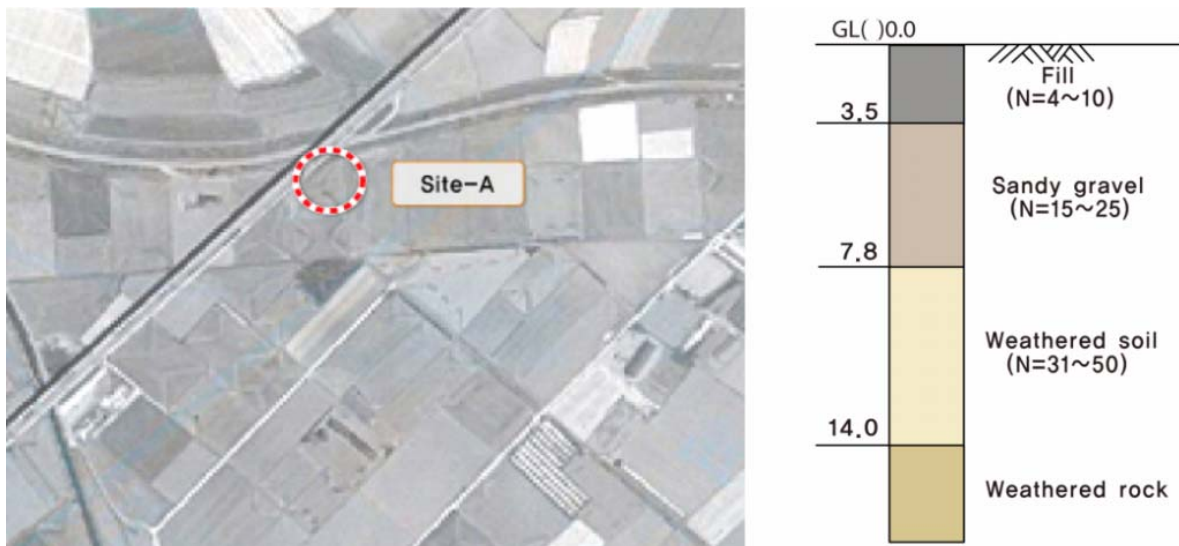


Figure 1. Location of the pile load test and geotechnical profile

3. MAKING AND CONSTRUCTION OF THE TEST PILE

Generally, the making process of PHC pile is; PC steel rod processing → template production → concrete pouring → PC steel rod tension → centrifugal forming → steam curing → prestress Induction → completion. As it is required to attach strain gauge to the PC steel rod before pouring concrete to observe load transfer, we cured the test pile in a low temperature, instead of a high temperature where gauge trouble can happen, we installed the strain gauge at intervals of 2m from upper 4m and 1m for the below of upper 4m in order to measure aspects of load transfer depending on shaft resistance.

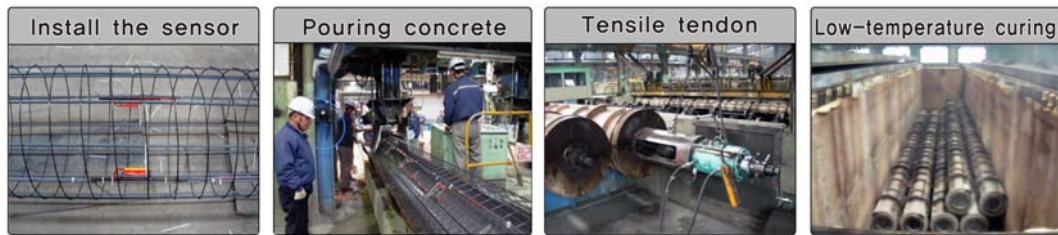


Figure 2. Process of making test pile

To construct the test pile, we excavated 4.7m which is a depth of bottom foundation to meet the conditions of bridge foundations.

Table 1. Characteristics of the test pile

Test pile	Diameter(mm)	Thickness(mm)	Length(m)	End of Pile
PHC pile	Ø600	90	11.0	Flat Shoe

When it comes to pile construction, we injected grout through the end of auger up to the required depth, after boring auger and casing reverse rotating by using SDA equipments. Then, we inserted the test pile into the boring hole and drove slightly it until the end of the pile reaches in-situ.

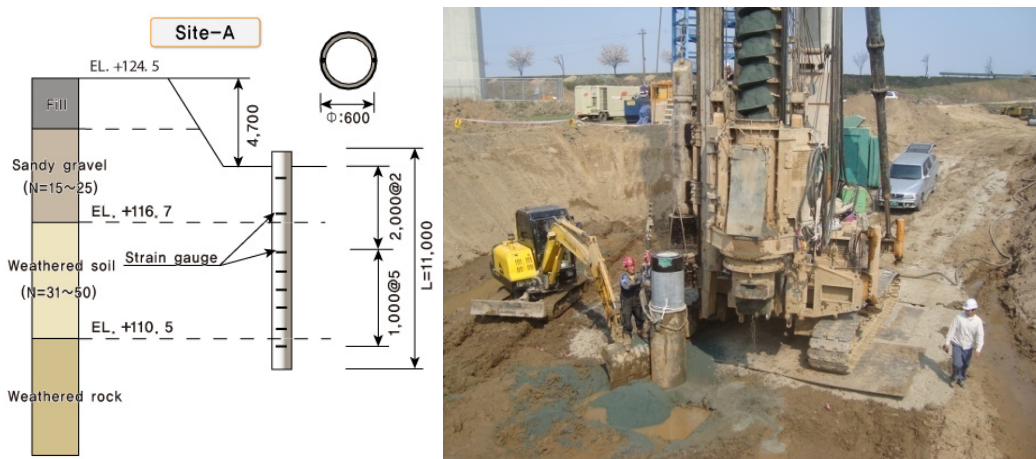


Figure 3. Location of strain gauge and picture of pile construction

We loaded the reaction of the pile loading test by using earth anchor. Earth anchor has allowable tensile force of 700KPa/EA and we loaded it in vertical direction not to allow eccentricity by constructing 8EA to be balanced in loading.

4. DYNAMIC LOADING TEST

4.1 PREPARATION

Dynamic loading test was operated to establish construction management standards going with calculating the bearing capacity and slight driving after building the pile. Right after the pile construction, end bearing capacity of the pile was predicted by committing the initial dynamic loading test(EOID, end of initial driving). Also, using the re-driving dynamic loading test(restrike), it was able to measure the shaft resistance measurement and the bearing capacity that was considered by setup effects. The test was operated after setting the gauge at the test pile and it was used ASTM D4945 as the reference.

- ① Constructed the test pile in a suitable length on the basis of the result from a boring in advance and made the pile protrude about 3D from the ground.
- ② Installed gauge that can estimate acceleration and stress of the pile 1.5D away from head of the pile.
- ③ Connected pile driving analyzer and the gauge, inputted the data and checked the gauge.
- ④ Estimated the final penetration amount and data by driving.

4.2 ANALYSIS OF DYNAMIC LOADING TEST RESULTS

We dropped 50kN Drop Hammer with SDA equipments from 1.5m high and started dynamic loading test when final penetration amount is 5.0mm. As a result, the end bearing capacity was 2,136kN and after a few days(approximately 7 days) when was enough to cure the grout, we found out that shaft resistance of the pile was 1,516kN when we tested from 3.0m high using the same Hammer.

Table 2. Conditions of dynamic loading test

Type		Drop Height (m)	Final Penetration Amount (mm)	Compressive Stress (kPa)		
				Head of Pile	End of Pile	Maximum Value
SDA, ϕ PHC(600)	E.O.I.D	1.5	5.0	2.16	1.69	2.16
	Restrike	3.0	-	2.73	1.73	2.73

Table 3. Results of dynamic loading test

Type	Driving Energy (kN•m)	Drive Efficiency (%)	Soundness Index (%)	MQ	CAPWAP Method			Bearing Capacity(kN)
					Ru (kN)	Rs (kN)	Rb (kN)	
E.O.I.D	37.2	50	100	3.73	2,285	148	2,136	3,652
Restrike	44.2	30	100	2.63	2,369	1,516	853	

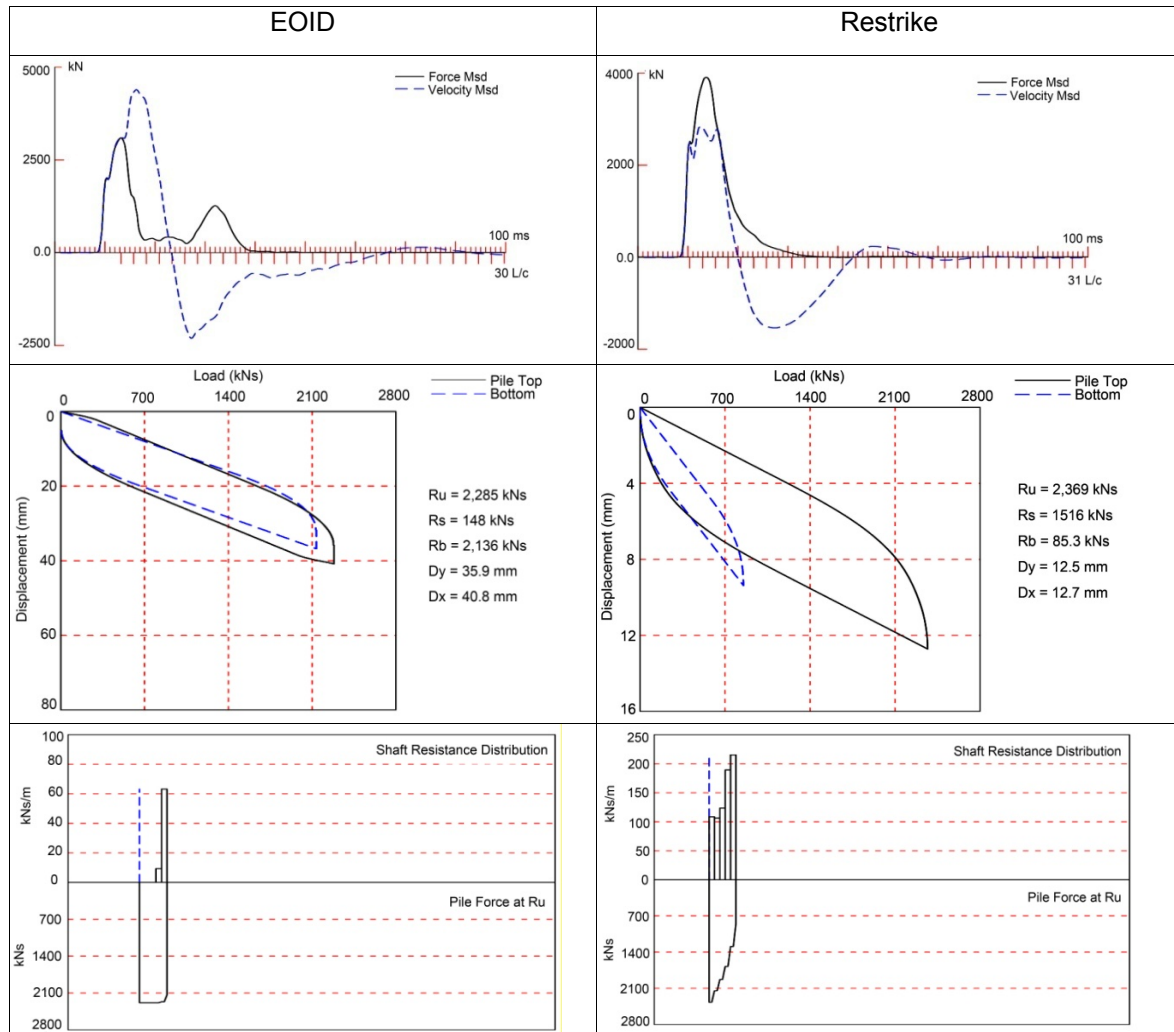


Figure 4. Analysis of dynamic loading test result by CAPWAP

The maximum compressive stress was 2.73kPa which is below the allowable value, showing that there was not any pile damage due to drive. The analysis by CAPWAP and PDA is as following.

Depending on the conditions of the ground, shaft resistance becomes large because embedded pile is cured by injecting grout after inserting the pile into boring. As time elapsed, after the pile construction, it became difficult to estimate end bearing capacity, as driving energy of the light hammer with SDA equipments is so low that it could exceed shaft resistance. As you can see the test result from the table 2 and 3, we did not get enough value of end bearing capacity, in terms of re-

driving dynamic loading test(restrike) and had difficulties in reflecting setup effects on end bearing capacity.

Through this test, we found out that it is required to have proper combinations of initial dynamic loading test(EOID) and re-driving dynamic loading test(restrike) to estimate the capacity by SDA equipment. Therefore, we estimated the pile bearing capacity by combining end bearing capacity from the former and shaft resistance from the later. As a result, the end bearing capacity was 2,136kN, the shaft resistance was 1,516kN and the bearing capacity was 3,652kN.

5. STATIC LOADING TEST

5.1 LOADING OF STATIC LOADING TEST

Static loading test was operated as a repetitive loading test referring to ASTM standard. Generally, load of test is planned on the basis of 200% of design load. In this test, however, we arranged the load 5,000kN to analyze the maximum bearing capacity of the pile from yield and ultimate load of the pile.

5.2 PREPARATION

As we planned the maximum load of static loading test is over 5,000kN, we designed the 11.0m pile to meet the conditions of the ground to protect the head from being broken when we cut the pile which is protrude from the ground,

- ① Set the load jack and the test beam on the test pile.
- ② Make possible to load by hydraulic jack connecting the reaction anchor and test beam.
- ③ Install the strain gauge on the two-way to measure the settlement of the load.
- ④ Practice the load test maintaining the load regularly by using the load cell.



Figure 5. View of static loading test

5.3 ANALYZING METHOD

The Analysis of bearing capacity can be divided into two methods which are on the basis of standard settlement, yielding and ultimate load. In this test, we used analyzing methods of yielding load and based on residual settlement.

Analysis based on the residual settlement was 6.3mm referring to AASHTO standard and American Bridge Design, and analysis based on the yielding load was measured by P-S, Log P-Log S method.

5.4 ANALYSIS

Static loading test was ended at 5,250kN which is the maximum test load, as represented above. At that time, the total settlement was 37.83mm, the residual settlement was 25.82mm and the elastic settlement was 12.01mm. There was displacement of approximately 6~7mm at intervals of 1,000kN increase, below the load of 4,200kN but, when the load above the point, there was of 15~16mm, approximately. Therefore, it did not reach to ultimate load in P-S curve and we decided the point as yielding load because, the slope pattern of P-S curve is changing at 4,200kN.

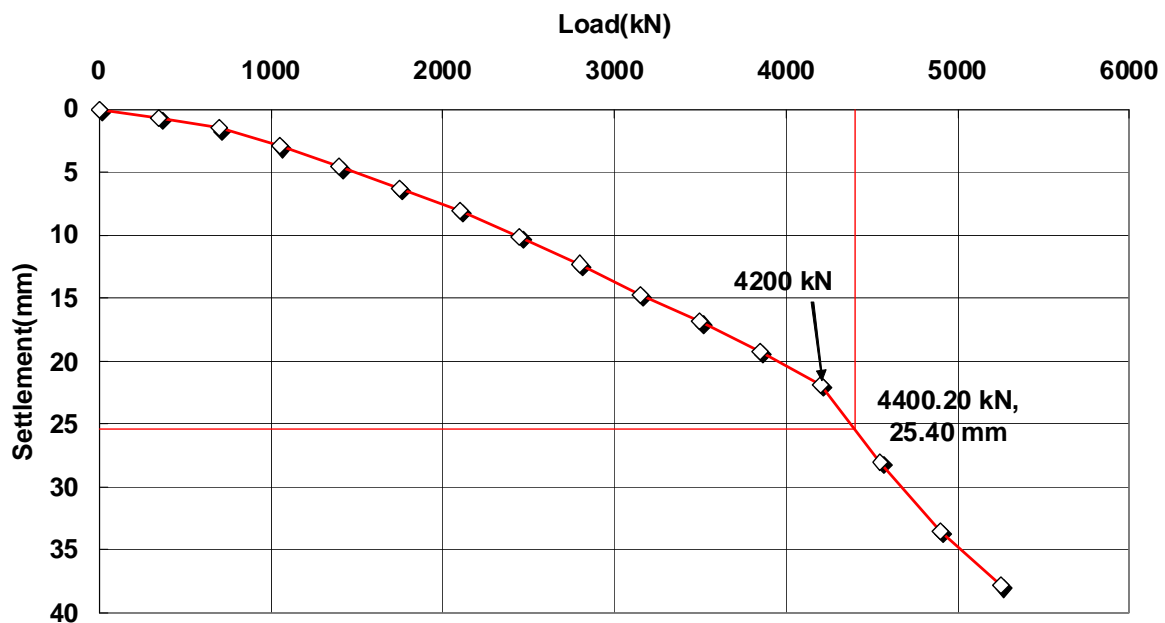


Figure 6. Result of static loading test (P-S curve)

In order to analyze the standard of residual settlement, we classified total settlement graph into elastic and residual settlement, as you can see on Figure 7. Although the elastic settlement curve is being uniform depending on the increase of load, the residual settlement is changing rapidly over 4,200kN which can be classified clearly as yielding load.

From this graph, we analyzed only residual settlement curve with the exception of elastic settlement in order to compute bearing capacity based on the standard of residual settlement. From

the curve, calculating the bearing capacity is finding the load at 6.33mm which is standard of residual settlement, and the following load was 2,761kN.

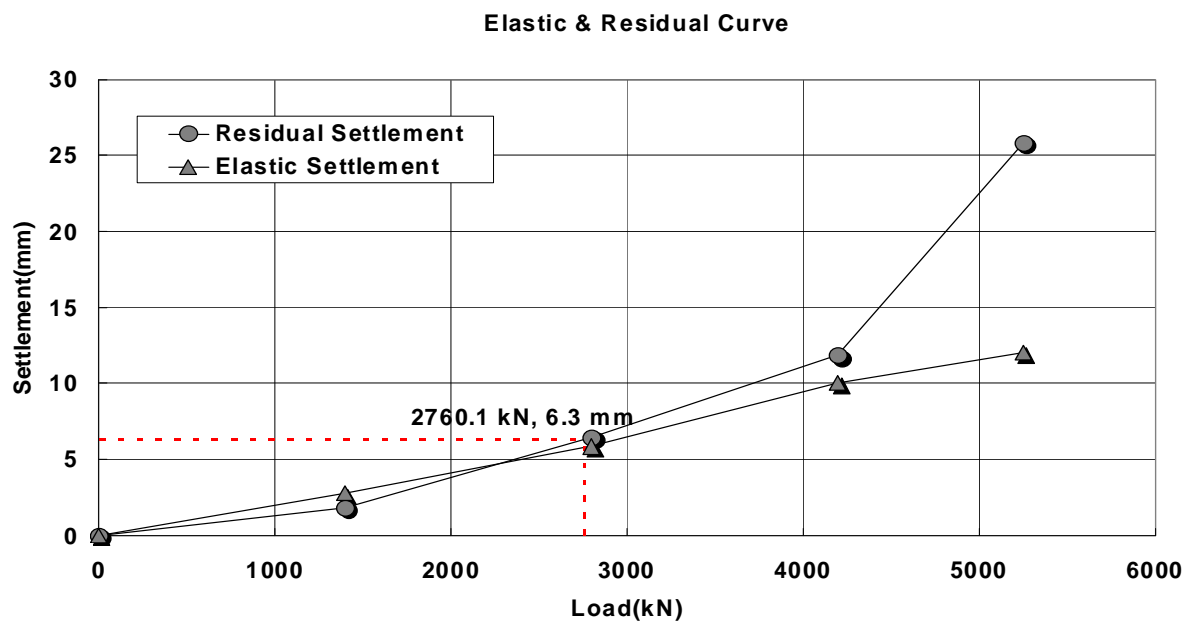


Figure 7. Analysis of residual and elastic settlement

Also, you can find out that the curve is going upward near at 4,200kN load in Figure 8.

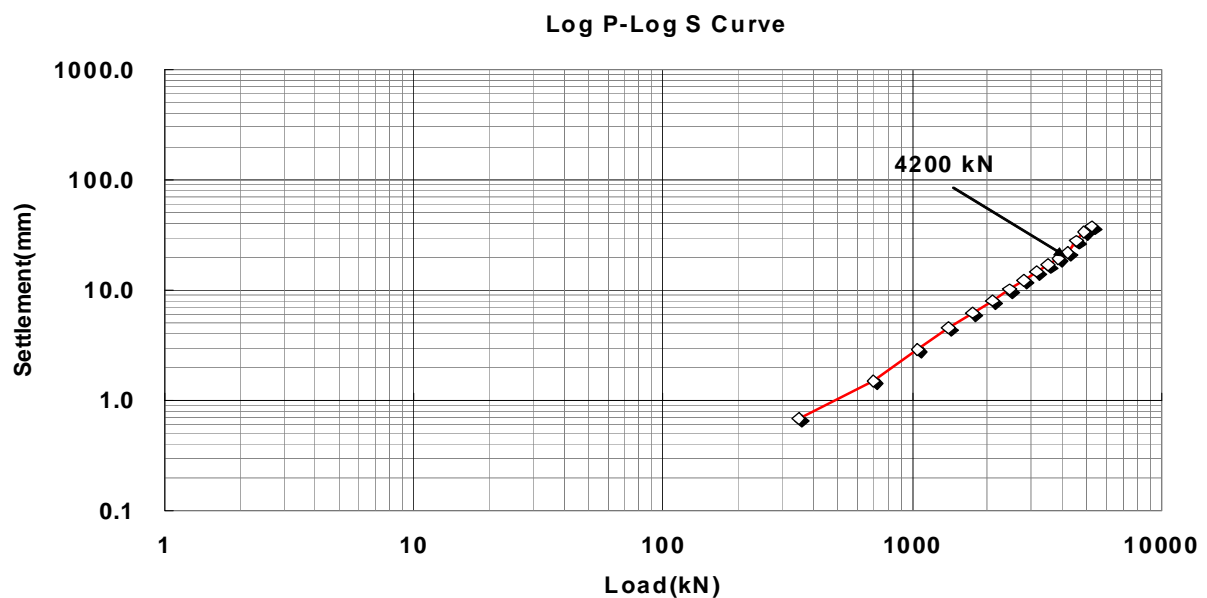


Figure 8. Result of static loading test (Log P-Log S curve)

When it comes to analysis of bearing capacity with the standard of residual settlement, it was estimated at 2,671kN, and the result of analyzing yield load was estimated at 4,200kN, which shows big difference from these two analysis processes. From the methods, installing end of the pile in the stiff ground is a reason of the difference. In general, load-settlement curve has a gentle feature until it reaches ultimate load because of the stiff ground. Thus, it is estimated that considerably heavy load was done in the test result too.

6. ANALYSIS OF LOAD TRANSFER

During the pile loading test, shaft resistance can be grasped from measuring the depth of the operation of the pile in the strain gauge which is installed on the pile. Moreover, the upright capacity can be predicted on the lines of increasing load by the result and the comparative examination through the shaft resistant, the characteristic of load supporting in end bearing capacity, dynamic loading test, and static loading test.

In the test, it has loaded until 5,250kN for analyzing load transfer and compressive stress is measured in each position from laying 16 strain gauges during pile production. As a result, figure 9 indicates that it upholds mostly by shaft resistance under 2,100kN. In a meantime, the pile's end bearing capacity is rarely occurred. However, the capacity increases when the excess of load to end of pile transferred. At that time, residual displacement occurred approximately 6~7mm.

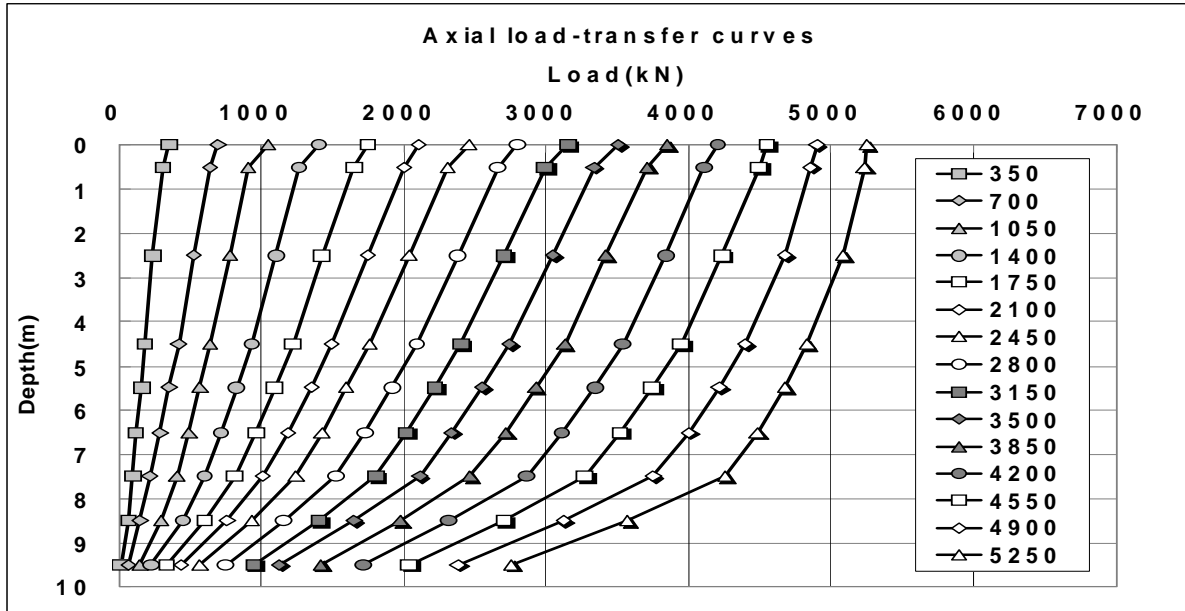


Figure 9. Axial load transfer curves

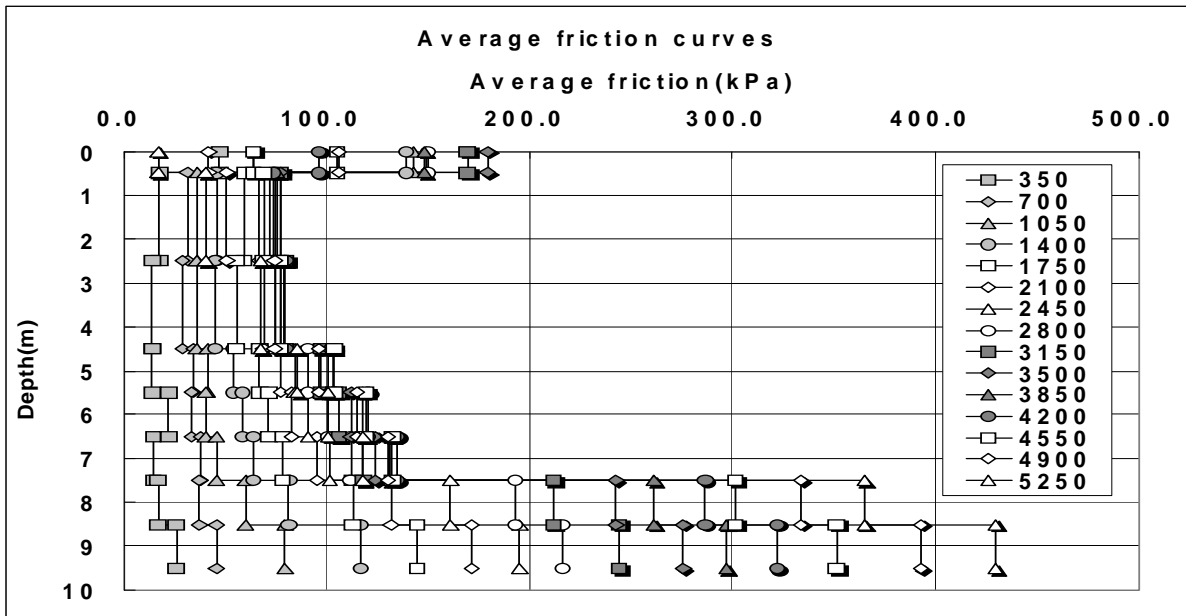


Figure 10. Average friction curves

In figure 11, 12 and 13, when analyzing the load transfer curve according to the depth, we can find extreme shaft resistance not only in a small displacement at the top of the ground but also in a large displacement at the stiff ground at bottom. It is estimated that the increase of the shaft resistance, especially, at about 7.5m depth of weathered soil layer and weathered rock layer. The following is t-z curve (frictional force-displacement curve) described by using axial load-transfer curve.

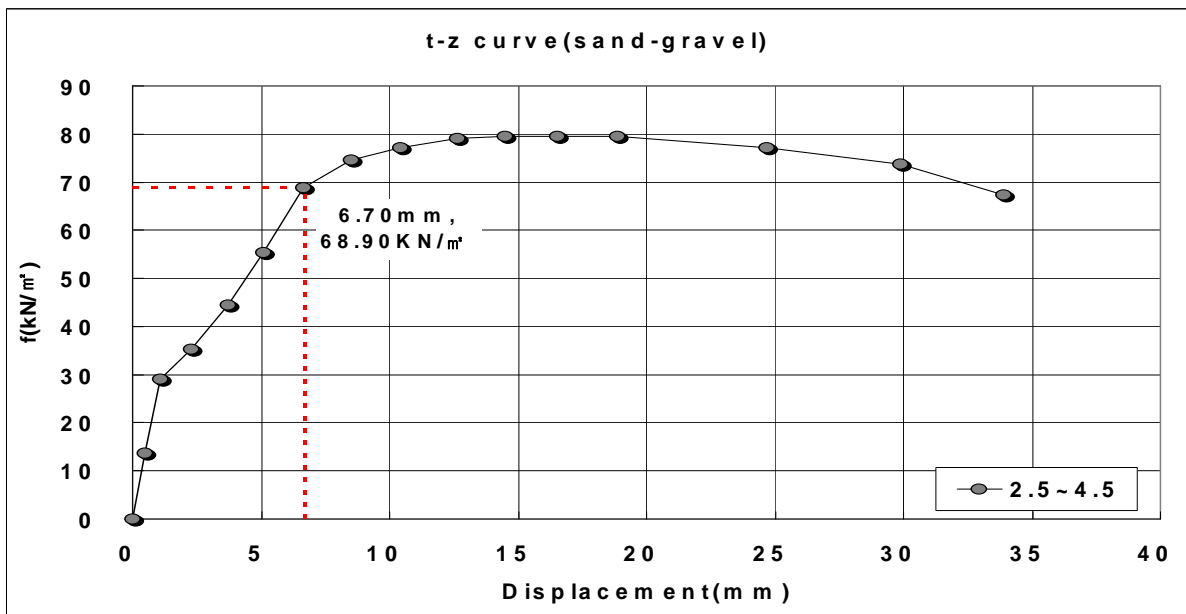


Figure 11. T-Z curve (depth: 2.5~4.5m)

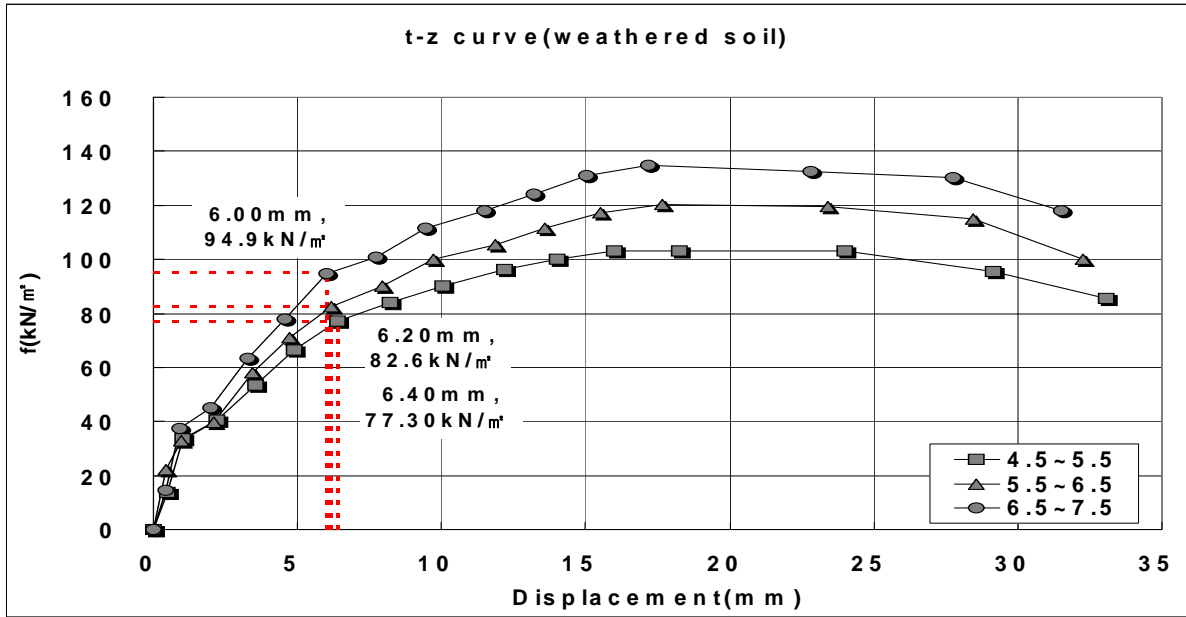


Figure 12. T-Z curve (depth: 4.5~7.5m)

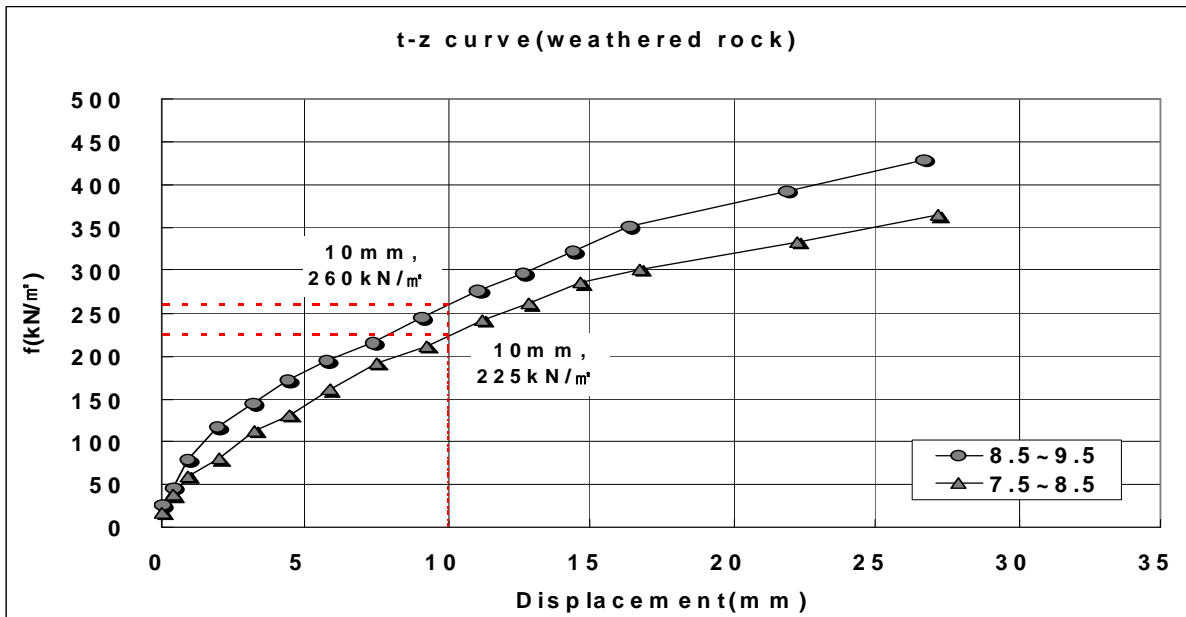


Figure 13. T-Z curve (depth: 7.5~9.5m)

As a result, in the upper fill and the weathered soil layer, the curve shows the extreme pattern over regular displacement but, in the bottom part of weathered soil layer and weathered rock layer where is stiff, the shaft resistance are continuously increasing as displacement increases. At the upper part of the ground, yield state is seen at about 6 ~ 7mm and ultimate state is seen at approximately 11 ~ 17mm.

We analyzed the result of lower weathered soil layer and weathered rock layer based on the standard of Vesic's proposal 10mm(1977, absent of pile's types, diameter and conditions of the ground).

Table 4. Analysis of T-Z curve

Type	Depth (m)	Maximum Frictional Resistance (kN/m ²)	Applying Frictional Resistance (kN/m ²)
Fill & Sandy gravel	2.5~4.5	79.6	79.6
weathered soil layer	4.5~5.5	103.5	103.5
	5.5~6.5	119.9	119.9
	6.5~7.5	134.8	134.8
	7.5~8.5	365.0	225.0
weathered rock layer	8.5~9.5	429.7	260.0

7. CONCLUSION

The analysis of dynamic loading test, static loading test and load transfer of the PHC pile lead to the following conclusions.

- 1) When layer of the end of pile is stiff, there is a great difference of bearing capacity between residual settlement and yield load and this result usually shows a gentle settlement curve. In order to reach the yield point, a large load is required. When the end of pile upholds to stiff ground, a big difference of the bearing capacity is occurred according to analyzing method of Loading Test. Thus, it is important to select the appropriate analysis method regarding the degree of sensitivity of the upper structure about the settlement.
- 2) The analysis of load transfer lead to the result that shaft resistance supports most of the load within 6~7mm areas of ultimate load. The additional load which passes over 11~17mm, where it is a displacement corresponding to ultimate load is delivered to the end of the pile, proportionately. At this time, the residual settlement which corresponds to the ultimate load appeared at about 6~7mm degree. The result for the test shows that shaft resistance upholds overwhelmingly by about 6~7mm degree. When there is displacement, we can find out that the load is delivered to the end.
- 3) In terms of embedded construction, after completing the pile, shaft resistance becomes large depending on the ground conditions. At that time, it is difficult to analyze the end bearing capacity with SDA equipments because the falling energy is small. Thus, when it comes to calculating the bearing capacity by dynamic loading test with the SDA equipments, you have to estimate end bearing capacity through the initial dynamic loading test(EOID) right after the

pile construction and calculate shaft resistance through re-driving dynamic loading test(restrike) after the grout is cured enough. Finally, we can get the bearing capacity of the pile by combining them.

However, the calculating method of combination excludes Set-Up effects. Therefore, the research and investigation of the dynamic loading test with driving energy is necessary.

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